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(54) **OPHTHALMIC ILLUMINATION SYSTEMS, DEVICES, AND METHODS**

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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,889,348 B2 * 2/2011 Tearney A61B 1/043 356/451
2002/0036904 A1 * 3/2002 Kawashima G03F 7/7005 362/276

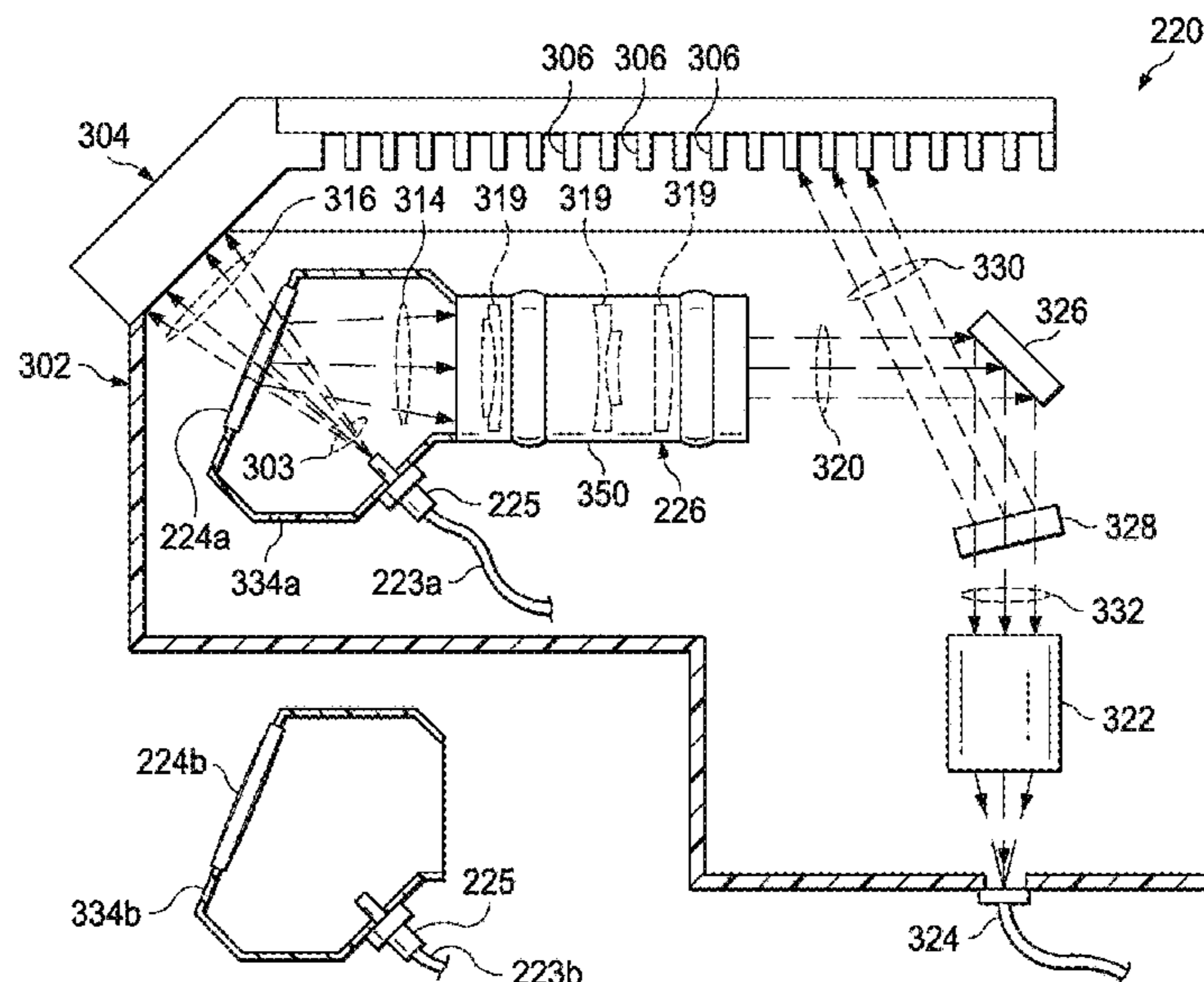
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Primary Examiner — Jordan M Schwartz

(57) **ABSTRACT**

Systems, apparatuses, and methods of and for an ophthalmic illumination system are disclosed. In an exemplary implementation, an ophthalmic illumination system includes a collimator having at least one lens. The system includes a first mirror arranged to reflect light towards the collimator. The first mirror is configured for use with a first light source that emits a first light beam having a first parameter. The system includes a second mirror arranged to reflect light towards the collimator. The second mirror is configured for use with a second light source emitting a second light beam having a second parameter that is different than the first parameter. The second mirror is shaped and arranged to cause a reflected portion of the second light beam to have the first parameter. The first mirror and the first light source, and the second mirror and the second light source, are separately usable with the collimator.

6 Claims, 7 Drawing Sheets



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(51) **Int. Cl.**

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<i>G02B 6/24</i>	(2006.01)
<i>G02B 6/36</i>	(2006.01)
<i>F21V 8/00</i>	(2006.01)
<i>A61F 9/007</i>	(2006.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2006/0007538	A1 *	1/2006	Robinson	G02B 27/102 359/487.04
2016/0089024	A1 *	3/2016	Katashiba	A61B 3/12 351/206
2016/0128557	A1 *	5/2016	Papac	A61B 3/0008 600/249
2018/0007936	A1 *	1/2018	Garrett	A61L 2/0047
2018/0360302	A1 *	12/2018	Thomsen	A61B 3/0008

* cited by examiner

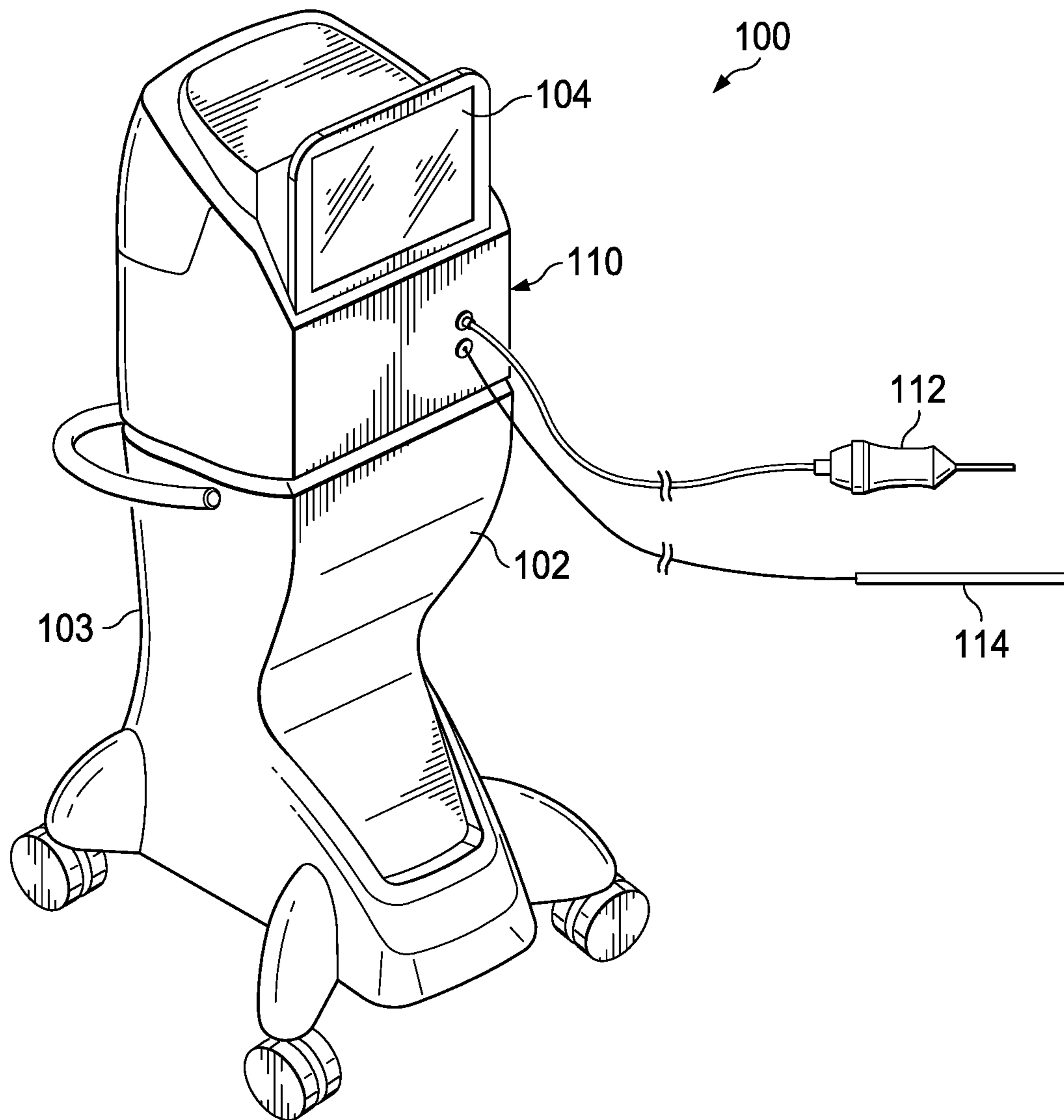


Fig. 1

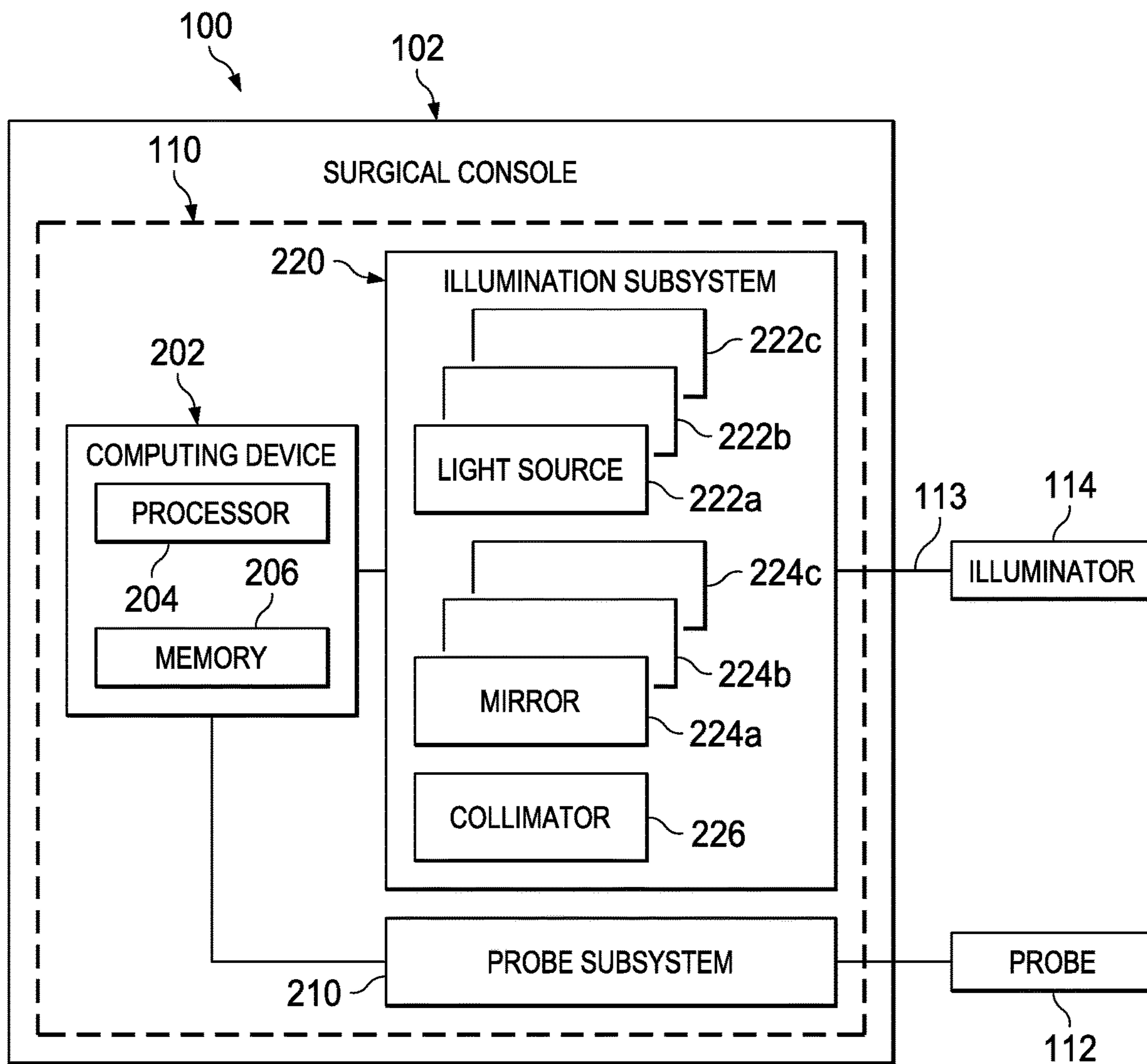


Fig. 2

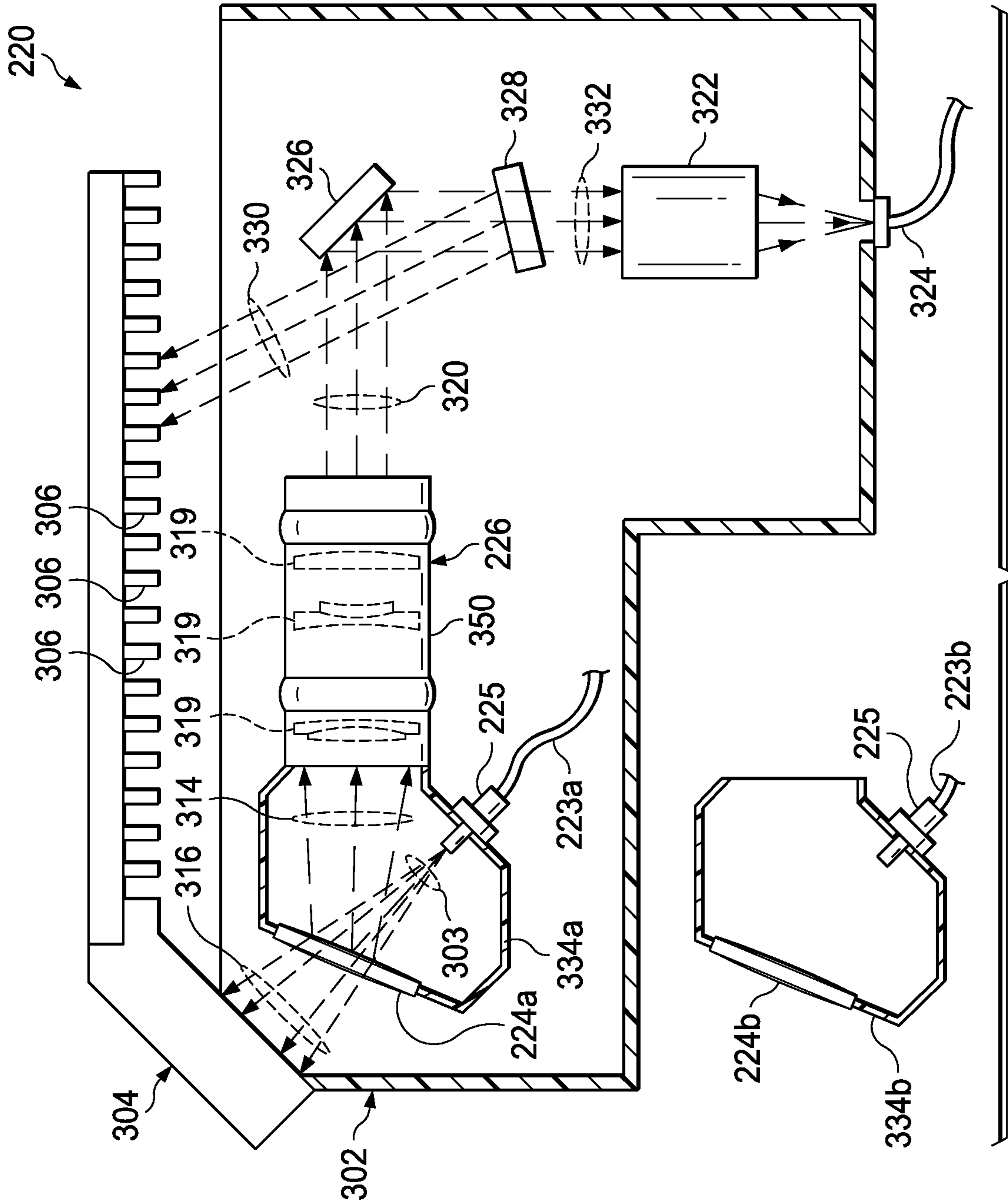


Fig. 3

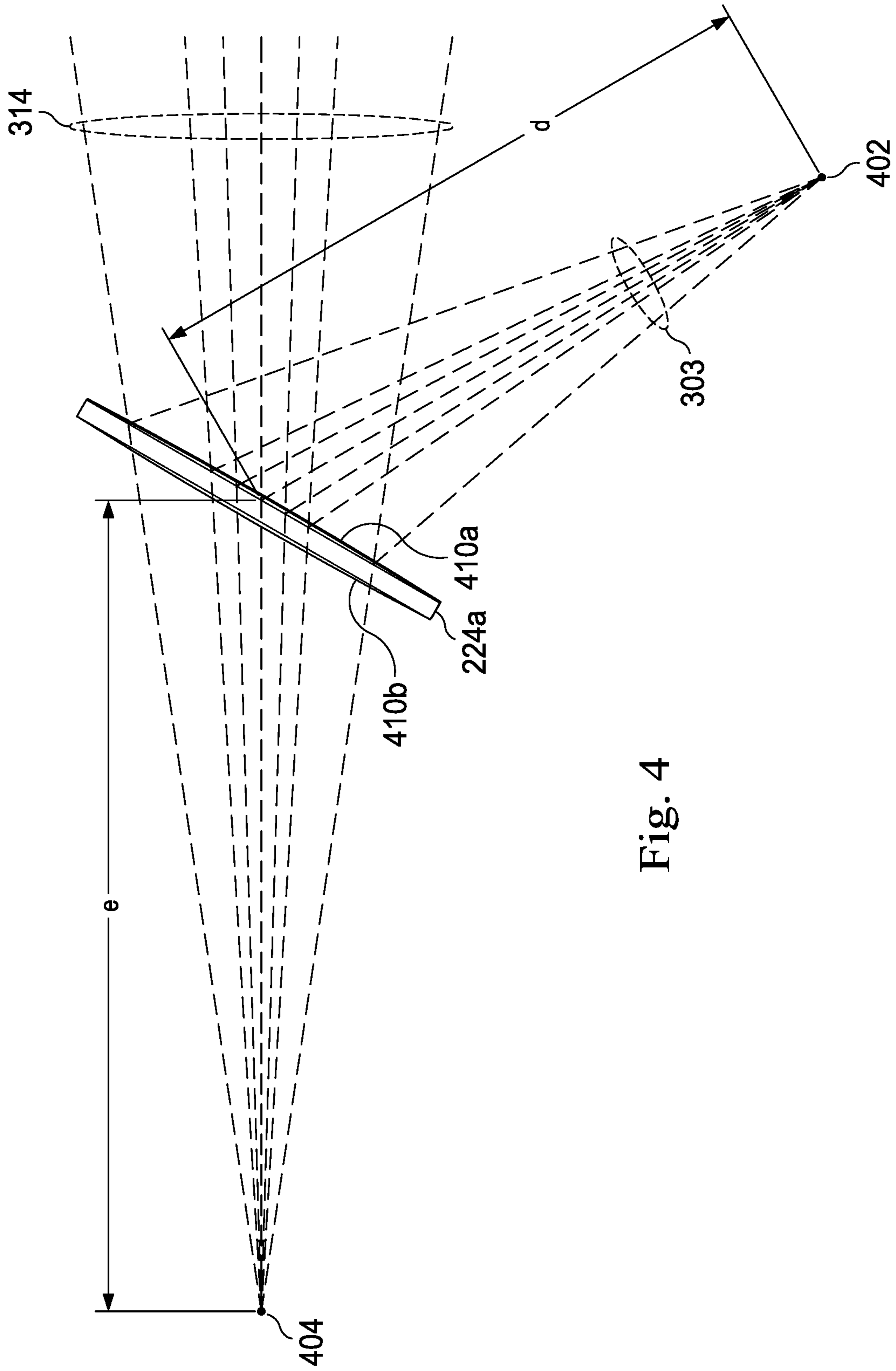


Fig. 4

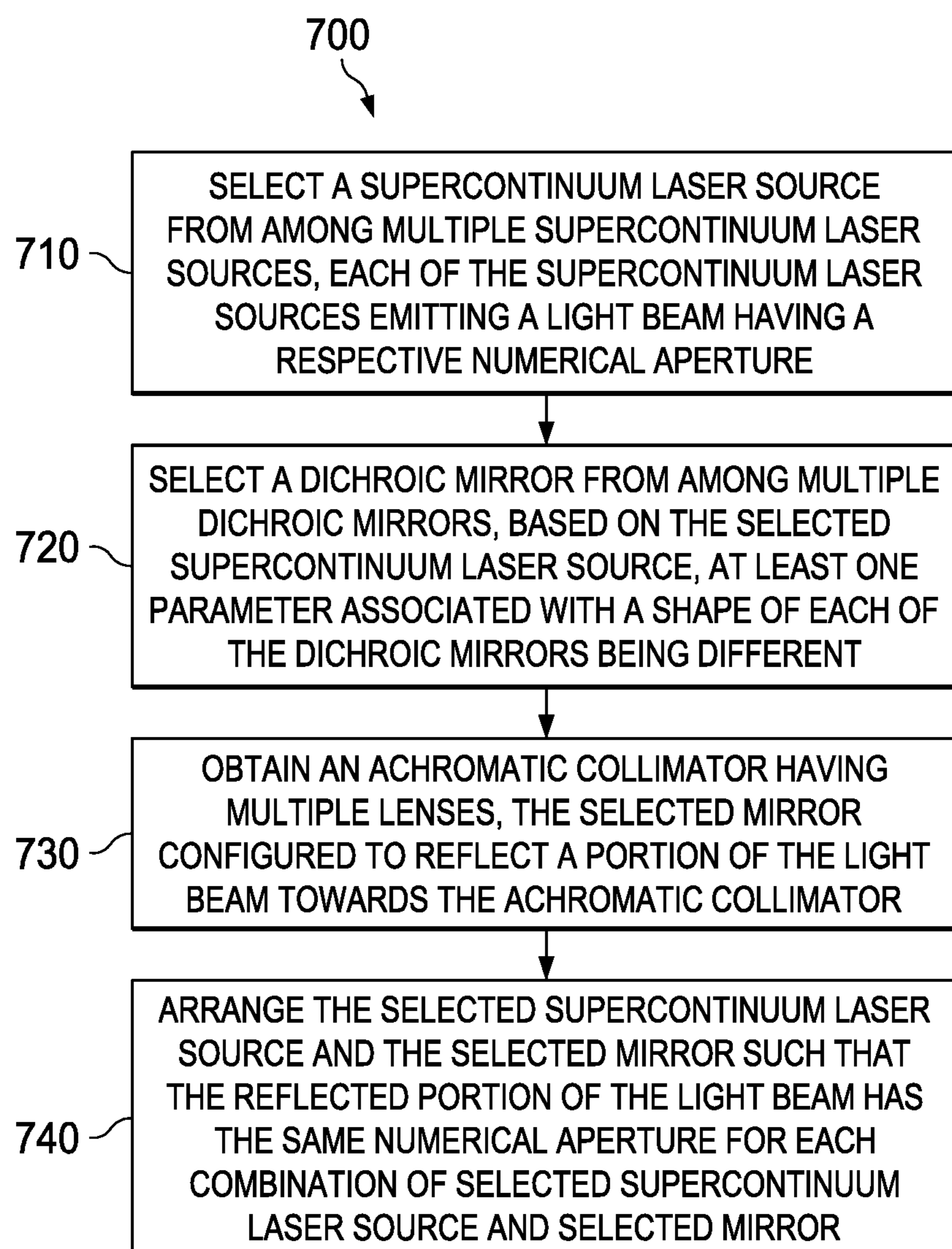


Fig. 7

OPHTHALMIC ILLUMINATION SYSTEMS, DEVICES, AND METHODS

This application is a divisional application of application Ser. No. 15/051,422, filed Feb. 23, 2016, which claims the benefit of U.S. Provisional Application No. 62/268,359, filed Dec. 16, 2015, the contents of both being incorporated herein by reference in their entirety.

TECHNICAL FIELD

The present disclosure is directed to ophthalmic illumination devices, systems, and methods. More particularly, but not by way of limitation, the present disclosure is directed to devices, systems, and methods of maintaining the same numerical aperture for a light beam transmitted towards a surgical field using different light source/mirror combinations.

BACKGROUND

Ophthalmic microsurgical procedures frequently require precision cutting and/or removing of various body tissues of the eye. During the procedures, ophthalmic illumination probes may provide illumination for the surgical field. A user, such as a surgeon or other medical professional, may insert the probe into the eye to illuminate the inside of the eye. The probe delivers light using an optical fiber. Typically, the probe is connected to an optical port of an ophthalmic illumination system. The ophthalmic illumination system may be part of a surgical console and includes a light source. The illumination system may also include other optical elements, such as a condenser, that facilitate coupling the light into the probe's optical fiber.

During assembly of the ophthalmic illumination system, manufacturers try to optimize various parameters of the light beam. These parameters may include coupling efficiency, which describes how well the light is coupled into probe's optical fiber. High coupling efficiency corresponds to the desirable transmission of relatively greater amount of undistorted light from the light source to the surgical field, via the probe. Low coupling efficiency corresponds to less light being transmitted to the surgical field, as well as the light that is transmitted having an undesired angular profile. Other parameters that affect system performance include how well the light is transmitted within the fiber and the angular profile of the output beam that is transmitted to the surgical field.

One or more of these parameters may be influenced by the numerical aperture ("NA") of the light beam. The NA is, generally speaking, a description of the width or diameter of a beam and may be referenced as a cone angle. The NA may also be used to describe the width or diameter of a beam that can be accepted by an optical fiber. For some light sources, such as a supercontinuum laser source, the NA of the beam is roughly proportional to wavelength. Thus, higher wavelength light has a higher NA and vice versa. Different light sources can also transmit light having different NAs. Differing beam diameters for different light sources and different wavelengths of light present challenges in manufacturing a system with consistent NA to consistently achieve high levels of coupling efficiency, high transmittance efficiency within the fiber, and desirable angular profiles for the output beam.

Various components of illumination systems, such as collimators, are typically designed to work best with light having a given beam diameter. For example, when a light

beam has a collimated beam diameter that is larger than the intended beam diameter, the cone angle of light focused into the fiber will be larger as well. In general, the nominal collimated beam diameter may be maximized to completely angularly fill the acceptance NA of the fiber. Therefore, a collimated beam diameter that is larger than nominal will result in loss of efficiency within the fiber. Even if the beam is efficiently coupled into the fiber, at its first encounter with the core/cladding interface on the cylindrical side surface of the fiber, the high angle rays of the high NA beam above the fiber acceptance NA will be lost in the cladding. Similarly, if the collimated beam diameter is less than the nominal value, the beam will efficiently couple into and be efficiently transmitted through the fiber. However, its beam NA will be less than nominal, and therefore the beam emitted from the distal end of the fiber will have an angular spread that is less than desired. In both circumstances, there is a penalty for not having the collimated beam diameter be constant with wavelength at the nominal desired value. Achieving a consistent collimated beam diameter with different light sources across different wavelengths can be difficult.

SUMMARY

According to one aspect, the present disclosure describes an ophthalmic illumination system including a collimator including a plurality of lenses. The system may include a first mirror arranged to reflect light towards the collimator. The first mirror may be configured for use with a first light source. The first light source may emit a first light beam having a first parameter. The system may also include a second mirror arranged to reflect light towards the collimator. The second mirror may be configured for use with a second light source. The second light source may emit a second light beam having a second parameter that is different than the first parameter. The second mirror may be shaped and arranged to cause a reflected portion of the second light beam to have the first parameter. The first mirror and the first light source, and the second mirror and the second light source, may be separately usable with the collimator.

Another aspect of the present disclosure is directed to an ophthalmic illumination system including a supercontinuum laser source emitting a light beam. The system may also include a mirror reflecting a portion of the light beam. The mirror may be a hyperbolic dichroic mirror or elliptical dichroic mirror. The system may also include an achromatic collimator having a plurality of lenses. The plurality of lenses may transmit the reflected portion of the light beam towards an eye of a patient.

A third aspect of the disclosure is directed to method of manufacturing an ophthalmic illumination system. The method may include selecting a supercontinuum laser source from among multiple supercontinuum laser sources. Each of the multiple supercontinuum laser sources may be arranged to emit a light beam having a respective numerical aperture. The method may also include selecting a dichroic mirror from among multiple dichroic mirrors, based on the selected supercontinuum laser source. At least one parameter associated with a shape of each of the dichroic mirrors may be different. The method may also include obtaining an achromatic collimator having multiple lenses. The selected mirror may be configured to reflect a portion of the light beam towards the achromatic collimator. The method may also include arranging the selected supercontinuum laser source and the selected mirror such that the reflected portion of the

light beam has the same numerical aperture for each combination of selected supercontinuum laser source and selected mirror.

The various aspects of the disclosure may include one or more of the following features. The collimator may comprise an achromatic collimator. At least one of the first mirror and the second mirror may comprise a hyperbolic dichroic mirror. The collimator and at least one of the first mirror and second mirror may be disposed within a surgical console. The first mirror may be disposed within a first housing, the second mirror may be disposed within a second housing, and at least one of the plurality of lenses of the collimator may be disposed within a third housing. The first housing and second housing may be sized and shaped to be interchangeably coupled to the third housing. The first and second parameters may be first and second numerical apertures, respectively. The first mirror may be spaced from the first light source by a first distance, and the second mirror may be spaced from the second light source by a second distance. The system may further include the first and second light sources. The first and second light sources may be separately usable with the collimator. At least one of the first and second light sources may be a supercontinuum laser source. At least one of the first mirror and the second mirror may comprise an elliptical dichroic mirror. The system may further include a surgical console. The supercontinuum laser source, the mirror, and the achromatic collimator may be disposed within the surgical console. The system may further include an endo-illuminator in communication with the surgical console. The endo-illuminator may deliver the reflected portion of the light beam into the eye of the patient.

The various aspects of the disclosure may also include one or more of the following features. Arranging the selected supercontinuum laser source and the selected mirror may include spacing the selected supercontinuum laser source and the selected mirror at a first distance. Another of the multiple supercontinuum laser sources and another of the multiple mirrors may be spaced at a second distance for the reflected portion of the light beam to have the same numerical aperture. Arranging the selected supercontinuum laser source and the selected mirror may include coupling the achromatic collimator and a housing comprising the selected supercontinuum laser source and the selected mirror. The selected mirror may be disposed within a first housing, another of the multiple mirrors may be disposed within a second housing, and the multiple lenses of the achromatic collimator may be disposed within a third housing. The first and second housings may be configured to be separately coupled to the third housing. The selected mirror may comprise a hyperbolic mirror. The selected mirror may comprise an elliptical mirror.

It is to be understood that both the foregoing general description and the following drawings and detailed description are exemplary and explanatory in nature and are intended to provide an understanding of the present disclosure without limiting the scope of the present disclosure. In that regard, additional aspects, features, and advantages of the present disclosure will be apparent to one skilled in the art from the following.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings illustrate embodiments of the systems, devices, and methods disclosed herein and together with the description, serve to explain the principles of the present disclosure.

FIG. 1 is an illustration of an example ophthalmic surgical system.

FIG. 2 is a block diagram of an example ophthalmic surgical system.

FIG. 3 is an illustration of an example illumination subsystem including a hyperbolic mirror.

FIG. 4 is an illustration of a portion of an example illumination subsystem.

FIG. 5 is an illustration of an illumination subsystem similar to that of FIG. 4 but annotated to show characteristics of a hyperbolic mirror.

FIG. 6 is an illustration of an illumination subsystem similar that of FIG. 3 but including an elliptical mirror.

FIG. 7 is a flow diagram of an example method of manufacturing an ophthalmic illumination system.

These figures will be better understood by reference to the following detailed description.

DETAILED DESCRIPTION

For the purposes of promoting an understanding of the principles of the present disclosure, reference will now be made to the implementations illustrated in the drawings and specific language will be used to describe them. It will nevertheless be understood that no limitation of the scope of the disclosure is intended. Any alterations and further modifications to the described devices, instruments, methods, and any further application of the principles of the present disclosure are fully contemplated as would normally occur to one skilled in the art to which the disclosure relates. In particular, it is fully contemplated that the features, components, and/or steps described with reference to one or more implementations may be combined with the features, components, and/or steps described with reference to other implementations of the present disclosure. For simplicity, in some instances the same reference numbers are used throughout the drawings to refer to the same or like parts.

The present disclosure relates generally to devices, systems, and methods for ensuring that a laser beam entering a collimator in an ophthalmic illumination system has the same or substantially the same numerical aperture (“NA”) regardless of the supercontinuum source from which the beam originates. A dichroic mirror that is hyperbolically or elliptically shaped is positioned relative to the light source such that the reflected portion of the light beam has the same NA even though the NAs of the beams emitted by the multiple supercontinuum sources are different. The shape of the mirror and the distance between the mirror and the light source may be selected to achieve the same NA for all mirror/light source combinations.

The devices, systems, and methods of the present disclosure provide numerous advantages. In particular, assembly line manufacturing of the ophthalmic illumination system is simplified because many components of the system, such as the collimator, may stay the same irrespective of different supercontinuum sources. Because the same collimator is used, the advantages of the collimator may be enjoyed for multiple supercontinuum sources. These advantages include good achromatic collimation with a near-diffraction limited collimated wavefront and a collimated beam diameter that is virtually constant with wavelength. These advantages allow for a high coupling efficiency to be obtained even though different supercontinuum sources may be used. Additionally, the systems described herein mitigate the undesired loss of transmittance within the optical fiber due to high angle rays being lost in the cladding as well as provide a desired angular profile for the output beam. The advantages also

provide one, such as a manufacturer, a greater flexibility in choosing among supercontinuum sources, based on, for example, cost, availability, and other factors, without sacrificing on performance.

FIG. 1 illustrates an example ophthalmic surgical system 100. The system 100 includes a surgical console 102, a probe 112, and an illuminator 114. The probe 112 and the illuminator 114 may be at least partially positioned within the surgical field or surgical site while a user performs surgical tasks on an eye of a patient. The system 100 may be used to perform various ophthalmic surgical procedures including an anterior segment procedure, a posterior segment procedure, a vitreoretinal procedure, a vitrectomy procedure, a cataract procedure, and/or other desired procedures. The surgical console 102 includes a mobile base housing 103 and an associated display screen 104 showing data relating to system operation and performance during a procedure. A distal portion of probe 112 may be inserted into the eye to treat an optical condition. For example, the probe 112 can be a cutting probe, a vitrectomy probe, a phacoemulsification probe, a laser probe, an ablation probe, a vacuum probe, a flushing probe, scissors, forceps, an infusion device, an aspiration device, and/or other suitable surgical device. The illuminator 114 may have a distal portion configured to be inserted into the eye and illuminate the tissue inside the eye during the surgical procedure. For example, the illuminator 114 may be an ophthalmic chandelier, spot illuminator, endo-illuminator, fiber optic light source, and/or other suitable surgical illumination device. The illuminator 114 may provide bright, background, broadband, and/or white light to illuminate the surgical field. While the probe 112 and the illuminator 114 are shown as distinct components, it is understood that the two may be integrated into a single surgical instrument in some implementations.

The surgical console 102 includes a control system 110 that is communicatively coupled to the probe 112 and/or the illuminator 114. For example, pneumatic, optical, and/or electrical supply lines may extend between and communicatively couple the control system 110 and the probe 112, and/or the illuminator 114. In some implementations, the supply lines may facilitate control and monitoring by also transmitting control signals, status signals, and/or other data between the surgical console 102 and the probe 112 and/or the illuminator 114.

An exemplary implementation of the ophthalmic surgical system 100, including additional structure of the control system 110 is illustrated in the block diagram of FIG. 2. The illustrated implementation of the control system 110 includes a computing device 202, a probe subsystem 210, and an illumination subsystem 220. In some implementations, including the implementation shown, the computing device 202 is integrated into the surgical console 102, while in other implementations the computing device 202 may be distinct and separate from the console 102. The computing device 202 includes a processing circuit having one or more processors 204 and memory 206. The processor 204 may execute computer instructions, such as those stored on the memory 206, to control various subsystems and their associated surgical devices. The memory 206, which is typically a semiconductor memory such as RAM, FRAM, or flash memory, interfaces with the processor 204. As such, the processor(s) 204 may write to and read from the memory 206, and perform other common functions associated with managing semiconductor memory 206. Processing circuit(s) of the computing device 202 may be integrated circuits with power, input, and output pins capable of performing logic functions. In various implementations, the processor 204 is

a targeted device controller, a microprocessor configured to control one or components of the surgical system 100 and/or a combination thereof. For example, the processor 204 may generate and transmit control signals to control activation and deactivation of the illumination subsystem 220 and/or the illuminator 114, as well as the intensity, wavelength, and/or other characteristics of light emitted by the illumination subsystem 220.

The probe subsystem 210 may include various components facilitating operation of the probe 112. In some implementations, the probe subsystem 210 may be in electrical communication with the computing device 202. In an implementation where the probe 112 is a pneumatically-actuated probe, when the probe 112 is pneumatically actuated, the probe subsystem 210 may include a pneumatic pressure source and/or a probe driver. In other implementations, the probe subsystem 210 may include various mechanical, electrical, piezoelectric, optical and/or other components for operation of the probe 112.

The illumination subsystem 220 includes a light source 222a, a mirror 224a, and a collimator 226. The light source 222a generates and/or otherwise provides light to the illuminator 114 via a conduit 113, such as an optical fiber. The conduit 113 may be operable to transmit light, optical signals, electrical signals, and/or data between the illumination subsystem 220 and the illuminator 114 in different implementations. The light source 222a may be in electrical communication with the computing device 202 and in electrical and/or optical communication with the illuminator 114. The light source 222a may be integrated in the surgical console 102, as shown in FIG. 2, or may be distinct and separate from the surgical console 102 in other implementations. In an exemplary implementation, the light source 222a is a supercontinuum laser source operable to provide bright, broadband, and/or white light to the illuminator 114 to illuminate the surgical field. Although light source 222a is primarily described as being a supercontinuum source, the present disclosure contemplates that light source 222a may include any suitable light source for producing a light beam that may be condensed into an optical fiber, as discussed below.

The mirror 224a may be configured to reflect light from the light source 222a towards the collimator 226. In some implementations, the mirror 224a is dichroic mirror that interacts with different light frequencies differently. For example, the mirror 224a may be a dichroic mirror that interacts with light in the visible spectrum differently than light in the infrared (“IR”) spectrum. The mirror 224a may be a cold mirror that transmits all or a portion of the light in the IR spectrum and reflects all or a portion of the light in the visible spectrum. The mirror 224a may be a hot mirror that transmits all or a portion of the light in the visible spectrum and reflects all or a portion of the light in the IR spectrum. The mirror 224a may be a flat dichroic mirror, a hyperbolic dichroic mirror, an elliptical dichroic mirror, and/or otherwise suitably shaped dichroic mirror. As described in greater detail below, the mirror 224a may be spaced from the light source 222a or an optical fiber transmitting light from the light source 222a by a selected distance.

The collimator 226 may include a plurality of lenses configured to align the light emitted by the light source 222a. In some implementations, the collimator 226 is an achromatic collimator operable to collimate light beams having components of different wavelengths.

The light beam transmitted by the light source 222a may be characterized by a cone half angle or numerical aperture

(“NA”). Formally, $NA_a = \sin(\frac{1}{2} \cdot \text{cone half angle}_a)$. Different light sources, such as light sources **222b** and **222c** may have different numerical apertures NA_b and NA_c , respectively. In an exemplary implementation, a given surgical console, such as surgical console **102**, includes one light source **222a** and one mirror **224a**. One or more components of the illumination subsystem **220**, such as the collimator **226**, may be selected, sized, shaped, positioned, and/or otherwise arranged for efficient operation with a light beam having a particular NA. As a result, using these components of the illumination subsystem **220**, such as the collimator **226**, with different light sources **222b**, **222c** is not desirable because of the adverse impact on coupling efficiency, undesired loss of transmittance within the fiber due to high angle rays being lost in the cladding, and/or an undesired angular profile of the output beam.

Generally, the light sources **222a**, **222b**, and **222c** may have emitted beam NAs of NA_a , NA_b , and NA_c , respectively. The light beams reflected off of the mirror (e.g., mirror **224a**, **224b**, or **224c**) may have beam NAs of NA'_a , NA'_b , NA'_c , respectively. In general, the primed NAs do not necessarily equal the unprimed NAs. However, for a given light source and a flat dichroic mirror, then $NA' = NA$. In some implementations, the collimator **226** may be configured to work efficiently with the NA_a of light source **222a**. In such implementations, the mirror **224a** may be a flat dichroic mirror so that $NA'_a = NA_a$. In other implementations, even though the collimator **226** may be designed to be used with light with NA_a , the light sources **222b**, **222c** may be implemented in combination with mirrors **224b**, **224c**, respectively. The light sources **222b**, **222c** and/or mirrors **224b**, **224c** may be sized, shaped, positioned, arranged, and/or otherwise configured so that the reflected beam entering the collimator **226** has the same NA_a that the collimator **226** is designed to work with. That is, when implemented with light sources **222b**, **222c**, the mirrors **224b**, **224c** may be configured to provide diffraction limited transformation of the wavefront of the reflected beam into the NA_a associated with light source **222a**. According to an aspect of the present disclosure, the mirrors **222b** and **222c** may be a hyperbolic or elliptical dichroic mirror to ensure that $NA'_b = NA_a$ and $NA'_c = NA_a$. Thus, regardless of the particular light source/mirror combination used, the reflected light entering the collimator **226** has the same NA.

The mirrors **224b**, **224c** may be a hyperbolic dichroic mirror, an elliptical dichroic mirror, a flat dichroic mirror, and/or otherwise suitably shaped dichroic mirror in various implementations. The size, parameters, and/or prescription defining the shape of the mirrors **224b**, **224c** may be different to account for the different NA_b , NA_c of light sources **222b**, **222c**. The distance between the mirror **224b** and the light source **222b**, as well as the distance between the mirror **224c** and the light source **222c**, may be different than the distance between the mirror **224a** and the light source **222a** to account for the different NA_b , NA_c of light sources **222b**, **222c**. Accordingly, different light sources **222b**, **222c** may be incorporated into the surgical console **102** without the need to change the collimator **226** or other optical components of the illumination subsystem **220**.

FIG. 3 illustrates an example implementation of the illumination subsystem **220**. One or more optical components may be mounted or otherwise fixed to a base plate **302**. Light from the light source (e.g., the light source **222a** in FIG. 2) may be transmitted via an optical fiber **223a** that is coupled to a housing **334a** at port **225**. Light beam **303** emitted by the optical fiber **223a** may be directed towards the mirror **224a**, which is coupled to and/or supported by the

housing **334a**. The light beam **303** includes light in the visible and IR spectrums. In implementations in which the mirror **224a** is a dichroic cold mirror, all or a portion of light in the visible spectrum (e.g., filtered beam **314**) may be reflected. All or a portion of light in the IR spectrum (IR portion **316**) passes through the mirror **224a**. The mirror **224a** may be oriented at an oblique angle relative to optical fiber **223a** such that the reflected visible light (filtered beam **314**) is directed towards subsequent optics in the illumination subsystem **220** (e.g., the collimator **226**). The IR portion **316** passes through the mirror **224a** and is incident upon all or a portion of beam dump/heat sink **304** having fins **306**.

In some implementations, packaging constraints, such as the need to have fiber **223a** in a different physical location than collimator **226**, may necessitate the mirror **224a** being tilted at an off-axis angle relative to the beam **303** emitted from the fiber **223a**. As indicated in FIG. 5, the incident angle α measured between the normal of a central, axial ray **331** in the beam **303** and a line **333** normal to mirror **224a** at a point where the central, axial ray **331** of the incident beam **330** intercepts the mirror **224a** may be equal to the exit angle α relative to the normal of that same ray as it reflects off the dichroic mirror **224a**. Referring again to FIG. 3, the mirror **224a** may be variously positioned relative to the fiber **223a** in different implementations such that the mirror **224a** reflects light emitted by the fiber **223a** towards the collimator **226**.

The filtered beam **314**, reflected by mirror **224a**, may be directed towards and/or incident upon the collimator **226**. The collimator **226** may include optics operable to generate a collimated light beam **320**, including a plurality of lenses **319**. The present disclosure contemplates that collimator **226** may comprise lenses, mirrors, gratings, filters, any suitable optics, or combination of optics operable to produce the collimated light beam **320**. In some implementations, portions of the light beam reflected by the mirror **224a** and collimated by the collimator **226** have the same collimated beam diameter regardless of the light source used and without variation based on wavelength.

The collimated light beam **320** generated by collimator **226** may be directed to a condenser **322** configured to focus or direct the collimated light beam **320** into an optical fiber **324**. The optical fiber **324** may be a component of the illuminator **114** and/or in optical communication with the illuminator **114** such that the collimated light beam **320** is transmitted to the surgical field. The condenser **322** may include one or more optical lenses, mirrors, gratings, filters, other optical components, and/or combinations thereof configured to focus the collimated light beam **320** into the optical fiber **324**.

In some implementations, the orientation of collimator **226** relative to condenser **322** may necessitate that collimated light beam **320** be redirected after exiting the collimator **226**. For example, illumination subsystem **220** may include a fold mirror **326** configured to reflect collimated light beam **320** toward the condenser **322**. In some implementations, a mirror **328** may be provided in the illumination subsystem **220** for additional IR filtering. The mirror **328** may be a hot mirror coated such that all or a portion of the remaining IR light of collimated light beam **320** (residual IR light **330**) is reflected while the visible portion **332** of collimated light beam **320** passes through to the condenser **322**. The mirror **328** may be oriented such that the reflected residual IR light **330** is directed towards beam dump/heat sink **304**.

The collimator **226** includes a distal housing **350**, a proximal housing **334a**, the collimating lenses **319**, and the

mirror **224a**. While the illustrated implementation shows a two-part housing, the collimator **226** may have a unitary, one-part housing or multi-part housing with more than two parts in different implementations. The distal housing **350** and the proximal housing **334a** may be removably/interchangeably coupled to one another to assemble the collimator **226**. For example, the distal housing **350** and the proximal housing **352a** may each include corresponding threads to facilitate engagement. In other implementations, a bracket or other mechanical component may be used to removably/interchangeably couple the distal housing **350** and the proximal housing **334a**.

The mirror **224a** may be coupled to and/or supported by the proximal housing **334a**. One or more lenses **319** may be disposed within, coupled to, and/or supported by one, the other, or both of the distal housing **350** and the proximal housing **334a**. In some implementations, all of the collimator lenses are disposed within the distal housing **350**, and the proximal housing **334a** includes no lenses. The collimator **226** may also include the port **225** to which a distal portion of the light source fiber **223a** is mechanically and/or optically coupled.

According to an aspect of the present disclosure, different light source(s) and different mirror(s) may be usable with the same collimator **226**, while maintaining high coupling efficiency, avoiding undesired loss of transmittance within the fiber due to high angle rays being lost in the cladding, and/or achieving a desired angular profile of the output beam. For example, during assembly of the illumination subsystem **220**, a manufacturer may choose from among multiple light source/mirror combinations for use with the collimator **226**. For example, FIG. 3 illustrates an alternative proximal housing **334b** that may replace the proximal housing **334a** in the illumination subsystem **220**. For example, the proximal housing **334b** may be coupled to the distal housing **350** instead of the proximal housing **334a**. An optical fiber **223b** may transmit light from a light source (e.g., light source **222b** in FIG. 2) that is different from the light source **222a** associated with optical fiber **223a**. The optical fiber **223b** is coupled to the port **225** of the proximal housing **334b**. Light emitted by the optical fiber **223b** is directed towards the mirror **224b**, which is coupled to and/or supported by the proximal housing **334b**. The mirror **224b** may be a hyperbolic, elliptical, flat, and/or otherwise suitably shaped dichroic mirror that transmits IR light and reflects visible light.

As similarly described with respect to the proximal housing **334a**, the proximal housing **334b** may be configured to be removably/interchangeably engaged with the distal housing **350**. While some components of the illumination subsystem **220** are described as being removably/interchangeably engaged, it is understood that in some implementations, the components are not intended to be separated after the illumination subsystem **220** has been manufactured. In that regard, the removable or interchangeable nature of components may refer to the ability of a manufacturer to select from among multiple components to assemble the illumination subsystem **220**. That is, a manufacturer may choose to couple the distal housing **350** to any of multiple different components, such as the proximal housings **334a**, **334b**.

While the light beams from light sources **222a**, **222b** have different NAs, the mirror **224b** may be positioned, sized, shaped, arranged, and/or otherwise configured such that light reflected from mirror **224b** has the same or substantially the same NA with which the collimator **226** is configured to work. For example, the specific parameters or prescription defining hyperbolic or elliptical features of the

mirror **224b** may account for the different NAs of the light sources **222a**, **222b**. Also, the optical fiber **223a** and the mirror **224a** may be separated by a first distance while the optical fiber **223b** and the mirror **224b** may be separated by a second distance, which may be different from the first distance, to account for the different NAs associated with light sources **222a**, **222b**. The light sources **222a**, **222b**, the optical fibers **223a**, **223b**, and/or the mirrors **224a**, **224b** may be coupled to and/or otherwise supported by proximal housings **334a**, **334b**, respectively, to facilitate the appropriate spacing between components.

FIG. 4 illustrates a portion of the illumination subsystem **220** including the mirror **224a**. The mirror **224a** includes two faces **410a**, **410b**. In various implementations, one, the other, or both faces **410a**, **410b** may be flat, hyperbolic, elliptical, and/or otherwise suitably shaped. In the illustrated implementation, the hyperbolic faces **410a**, **410b** may have a surface sag relative to a flat surface between approximately 1 μm and approximately 20 μm , approximately 5 μm and approximately 15 μm , and approximately 10 μm and approximately 15 μm , including values such as 12 μm , 13 μm , 13.5 μm , 13.7 μm , 13.9 μm , 14 μm , and/or other suitable values both larger and smaller.

The source location **402** may identify the actual or effective location from which light **303** from the light source **222a** is transmitted towards the mirror **224a**. For example, the source location **402** may correspond to the distal end of the optical fiber **223a**, the port **225**, or the location of the light source **222a** itself. The mirror **224a** may be spaced from the source location **402** by a distance d . The distance d may vary for mirrors **224a**, **224b**, and **224c**. For example, the distance d may be between approximately 1 mm and approximately 10 mm, approximately 1 mm and approximately 7 mm, and approximately 1 mm and approximately 5 mm, including values such as 3 mm, 3.2 mm, 3.5 mm, 3.8 mm, 4 mm, and/or other suitable values both larger and smaller. In some implementations, the distance d and the NA of the light source may be inversely related. Thus, the mirror **224a** and the source location **402** may be separated by a relatively smaller distance d when a light source having a relatively larger NA is used (and vice versa). As described below, in implementations in which the distance d varies, the distance e may remain the same.

The virtual source **404** may indicate the location from which the filtered beam **314** appears to diverge. In that regard, although the filtered beam **314** is in reality reflected off of the mirror **224a**, the beam **314** appears to diverge from behind the mirror **224a** at the virtual source **404**. The virtual source **404** is spaced from the mirror **224a** by the distance e . The location and position of the virtual source **404** may be optimized to facilitate efficient coupling of the light beam. In some implementations, the distance e may be the same for mirrors **224a**, **224b**, and **224c**. For example, the distance e may be between approximately 1 mm and approximately 10 mm, approximately 1 mm and approximately 7 mm, and approximately 1 mm and approximately 5 mm, including values such as 3 mm, 3.5 mm, 4 mm, 4.5 mm, 5 mm, and/or other suitable values both larger and smaller. For example, the mirror (e.g., mirrors **224a**, **224b**, **224c**) in different implementations may be placed at the same location relative to the collimator **226** (e.g., as measured by the distance of the central axial ray from the reflective surface of the mirror to the first collimator lens **319**). In such circumstances, in order for the reflected beam NAs from different light sources (e.g., the light sources **222b**, **222c**) to be the same or substantially similar to the beam NA with which the collimator **226** is designed to work (e.g., $\text{NA}'_b = \text{NA}_a$ and

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NA'_c=NA_a), then the distance e may be the same for all mirrors **224a**, **224b**, and **224c**. For implementations in which the emitted beam NAs of different light sources are different, then each distance d between the mirror and the light source may be different, as described above.

FIG. **5** illustrates a portion of the illumination subsystem **220** as in FIG. **4**. FIG. **5** additionally includes various annotations indicating values used to calculate the specific parameters of the hyperbolic surfaces **410a**, **410b** of the mirror **224a**. The parameters of the mirror **224a** may be selected to facilitate transformation of the reflected beam into a common NA for multiple supercontinuum sources. Formally, the shape of one or both faces **410a**, **410b** may be defined by

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1.$$

The parameter a may be defined by

$$\frac{f_2 - f_1}{2},$$

where f_1 is the distance between the source location **402** and the mirror **224a** along the z-axis and f_2 is the distance between the mirror **224a** and the virtual source **404** along the z-axis. In some implementations, the parameter a may be between approximately 0.1 mm and approximately 1 mm, or between approximately 0.1 mm and approximately 0.5 mm, including values such as 0.200 mm, 0.300 mm, 0.400 mm, and/or other suitable values both larger and smaller. In some implementations, the parameter f_1 may be between approximately 1 mm and approximately 5 mm, or between approximately 2 mm and approximately 3 mm, including values such as 2.500 mm, 2.700 mm, 2.710 mm, 2.720 mm, 2.722 mm, 2.724 mm, 2.726 mm, 2.730 mm, and/or other suitable values both larger and smaller. In some implementations, the parameter f_2 may be between approximately 1 mm and approximately 5 mm, or between approximately 3 mm and approximately 5 mm, including values such as 3.500 mm, 3.510 mm, 3.520 mm, 3.522 mm, 3.524 mm, 3.526 mm, 3.530 mm, and/or other suitable values both larger and smaller.

The parameter b may be defined by $\sqrt{c^2 - a^2}$, where

$$c = \frac{f_1 + f_2}{2},$$

which is half the distance between the source point **402** and the virtual source point **404**. In some implementations, the parameter b may be between approximately 1 mm and approximately 5 mm, or between approximately 2.5 mm and approximately 3.5 mm, including values such as 2.900 mm, 3.000 mm, 3.095 mm, 3.098 mm, and/or other suitable values both larger and smaller. In some implementations, the parameter c may be between approximately 1 mm and approximately 5 mm, or between approximately 2.5 mm and approximately 3.5 mm, including values such as 3.000 mm, 3.100 mm, 3.120 mm, 3.122 mm, 3.124 mm, 3.126 mm, 3.130 mm, and/or other suitable values both larger and smaller.

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A parameter R may be defined by

$$-\frac{b^2}{a},$$

which represents the base radius of curvature associated with the hyperbolic surfaces **410a**, **410b**. In some implementations, the parameter R may be between approximately -10 mm and approximately -30 mm, or between approximately -20 mm and approximately -25 mm, including values such as -23.00 mm, -24.00 mm, -25.00 mm, and/or other suitable values both larger and smaller.

A parameter k may be defined by

$$-1 - \frac{b^2}{a^2},$$

which represents the conic constant associated with the hyperbolic surfaces **410a**, **410b**. The parameter k may be referenced as the degree of deviation from a purely spherical surface. In some implementations, the parameter k may be between approximately -40 and approximately -70, or between approximately -55 and approximately -65, including values such as -60.00, -61.00, -62.00, and/or other suitable values both larger and smaller.

The angle α may describe the incident angle of light upon the mirror **224a** measured between the central, axial ray **331** in the beam **303** from the light source and/or associated optical fiber and a line **33** normal to mirror **224** at a point where the central, axial ray **331** of the incident beam **330** intercepts the mirror **224a**. The incident angle α may be equal to the exit angle α relative to normal of that same ray as it reflects off the mirror **224a**. In some implementations, the angle α may be between approximately 10° and approximately 40°, or between approximately 25° and approximately 35°, including values such as 29°, 30°, 31°, and/or other suitable values both larger and smaller. The angle β may describe the angle between the virtual portion of the filtered beam **314** and the z-axis. In some implementations, the angle β may be between approximately 10° and approximately 40°, or between approximately 20° and approximately 30°, including values such as 26.20°, 26.30°, 26.33°, 26.35°, and/or other suitable values both larger and smaller. The angle γ may describe the angle between the light emitted from the source location **402** and the z-axis. In some implementations, the angle γ may be between approximately 20° and approximately 50°, or between approximately 30° and approximately 40°, including values such as 33.50°, 33.65°, 33.67°, 33.69°, and/or other suitable values both larger and smaller.

FIG. **6** illustrates the illumination subsystem **220** similar to that FIG. **3**. In that regard, FIG. **6** includes many similar components as FIG. **3**, the descriptions of which are omitted. The illumination subsystem of FIG. **3** includes an elliptical dichroic mirror **602a**. The elliptical dichroic mirror **602a** is configured to transmit IR light and reflect visible light in the beam **332**. The elliptical dichroic mirror **602a** is also configured to provide diffraction limited transformation of the wavefront of the reflected beam **314** into the same NA_a for multiple light sources **222a**, **222b**, and **222c**. One or more faces of the elliptical dichroic mirror **602a** may be defined by

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1.$$

Similar to the hyperbolic dichroic mirrors described herein, other elliptical mirrors, such as, for example, elliptical dichroic mirrors, may be separately used with the collimator and different light sources **222b**, **222c**. The distance between the light sources **222a**, **222b**, **222c** (or the optical fibers **223a**, **223b**, etc.) and various elliptical dichroic mirrors may vary for each combination to allow the reflected beam to have the same NA_a . The specific parameters (e.g., the parameter a, the parameter b, etc.) of the various elliptical dichroic mirrors may also be selected for different light sources **222a**, **222b**, and **222c**. With an elliptical dichroic mirror **602a**, the filtered beam **314** has a convergence point **604** between the mirror **602a** and the collimator **226**.

FIG. 7 illustrates a flowchart of an example method **700** of manufacturing an ophthalmic illumination system. As illustrated, the method **700** includes a number of enumerated steps, but implementations of the method **700** may include additional steps before, after, and in between the enumerated steps. In some implementations, one or more of the enumerated steps may be omitted or performed in a different order.

At step **710**, the method **700** includes selecting a supercontinuum laser source from among multiple supercontinuum laser sources. Each of the supercontinuum laser sources emits a light beam having a respective numerical aperture. In that regard, the numerical apertures may be larger or smaller than one another. For example, a first laser source may have an NA at 650 nm at the $1.3 \times 1/e^2$ points that is approximately 0.1503. A second laser source may have an NA that is approximately 25% larger than the first laser source. While particular NA values are listed as examples, it is understood the present disclosure contemplates any suitable NA values.

At step **720**, the method **700** includes selecting a dichroic mirror from among multiple dichroic mirrors. In some implementations, the dichroic mirrors are hyperbolically, elliptically, and/or otherwise suitably shaped. At least one parameter defining the shape may be different between the multiple dichroic mirrors. The dichroic mirror may be selected based on the selected supercontinuum laser source (step **710**).

At step **730**, the method **700** includes obtaining an achromatic collimator having multiple lenses. The selected mirror (step **720**) may be configured to reflect a portion of the light beam from the selected supercontinuum laser source (step **710**) towards the achromatic collimator.

At step **740**, the method **700** includes arranging the selected supercontinuum laser source (step **710**) and the selected mirror (step **720**) such that the reflected portion of the light beam has the same numerical aperture for each combination of selected supercontinuum laser source and selected mirror. With reference to the example light sources described above, the supercontinuum laser source and the dichroic mirror may be arranged so that reflected portion of the light beam from the second laser source has the same NA as the first laser source. This is true even though the beam emitted by the second laser source has a 25% larger NA than the first laser source. In order to transform the reflected beam into a common NA, step **740** may include spacing the selected supercontinuum laser source and the selected mirror a first distance. Another of the multiple supercontinuum laser sources and another of the multiple mirrors may be spaced a second distance for the reflected portion of the light beam to have the same NA. Step **740** may include coupling the achromatic collimator and a housing comprising the selected supercontinuum laser source and the selected mirror. The housing may include or be coupled to at least a

portion of an associated optical fiber. In some implementations, the selected mirror may be disposed within a first housing and the multiple lenses of the achromatic collimator are disposed within a third housing. Another of the multiple mirrors may be disposed within a second housing. The third housing with the collimator may be separately coupled to the first and second housings, based on the selected mirror.

The method **700** can include additional steps in other implementations, such as obtaining a condenser. Collimated light may be directed to the condenser and into an optical fiber associated with a hand-held illuminator. In some implementations, the method **700** includes obtaining an IR filtering mirror and positioning the mirror within the illumination subsystem to remove IR light while allowing visible light to pass through. The method **700** can also include installing the illumination subsystem within a surgical console and performing a surgical procedure using the surgical console.

Persons of ordinary skill in the art will appreciate that the implementations encompassed by the present disclosure are not limited to the particular exemplary implementations described above. In that regard, although illustrative implementations have been shown and described, a wide range of modification, change, combination, and substitution is contemplated in the foregoing disclosure. It is understood that such variations may be made to the foregoing without departing from the scope of the present disclosure. Accordingly, it is appropriate that the appended claims be construed broadly and in a manner consistent with the present disclosure.

What is claimed is:

1. A method of manufacturing an ophthalmic illumination system, the method comprising:

selecting a supercontinuum laser source from among multiple supercontinuum laser sources, each of the multiple supercontinuum laser sources being arranged to emit a light beam having a respective numerical aperture;

selecting a dichroic mirror from among multiple dichroic mirrors, based on the selected supercontinuum laser source, at least one parameter associated with a shape of each of the dichroic mirrors being different;

obtaining an achromatic collimator comprising a lens, the selected mirror configured to reflect a portion of the light beam towards the achromatic collimator; and

arranging the selected supercontinuum laser source and the selected mirror such that the reflected portion of the light beam has the same numerical aperture for each combination of selected supercontinuum laser source and selected mirror.

2. The method of claim **1**, wherein the arranging the selected supercontinuum laser source and the selected mirror includes spacing the selected supercontinuum laser source and the selected mirror a first distance, wherein another of the multiple supercontinuum laser sources and another of the multiple mirrors is spaced a second distance for the reflected portion of the light beam to have the same numerical aperture.

3. The method of claim **1**, wherein arranging the selected supercontinuum laser source and the selected mirror includes coupling the achromatic collimator and a housing comprising the selected supercontinuum laser source and the selected mirror.

4. The method of claim **3**, wherein the achromatic collimator comprises multiple lenses, and wherein the selected mirror is disposed within a first housing, another of the multiple mirrors is disposed within a second housing, and the multiple lenses of the achromatic collimator are disposed

within a third housing, the first and second housings configured to be separately coupled to the third housing.

5. The method of claim 1, wherein the selected mirror comprises a hyperbolic dichroic mirror.

6. The method of claim 1, wherein the selected mirror comprises an elliptical dichroic mirror.

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